(54) DUAL CHAMBER PACING SYSTEM WITH CONTINUAL ADJUSTMENT OF THE AV ESCAPE INTERVAL SO AS TO MAINTAIN OPTIMIZED VENTRICULAR PACING FOR TREATING CARDIOMYOPATHY

ZWEIKAMMER-SCHRITTMACHER-ANORDNUNG ZUR KONTINUIERLICHEN REGELUNG DES AV ZEITINTERVALLES MIT DEM ZIEL, OPTIMIERTE STIMULIERUNG ZUR BEHANDLUNG VON KARDIOMYOPATHIEN ZU ERREICHEN

SYSTEME DE STIMULATION CARDIAQUE BI-CAVITE PERMETTANT LE REGLAGE CONTINU DE L'INTERVALLE DE L'ECHAPPEMENT AURICULO-VENTRICULAIRE DE FAÇON A ENTRETENIR UNE STIMULATION VENTRICULAIRE OPTIMALE PERMETTANT DE TRAITER LA MYOCARDIOPATHIE

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Description

This invention relates to cardiac pacing systems generally and, in particular, to dual chamber cardiac pacing systems for delivering ventricular pacing pulses synchronized to atrial signals so as to benefit patients with cardiomyopathy and other forms of congestive heart failure and, in particular, patients with Hypertrophic Obstructive Cardiomyopathy (HOCM).

Hypertrophic Obstructive Cardiomyopathy is characterized by a narrowed left ventricular outflow tract (LVOT), which causes a significant increase in the subaortic pressure gradient. The narrowed LVOT is caused by an increased thickness of the interventricular septum which obstructs blood flow during systole, or at the time of cardiac output.

Symptomatic improvement of patients with HOCM can be obtained in some cases with the use of standard pharmacotherapy. However, drugs in use for this therapy have disadvantages which have been cited in the literature. Likewise, surgical intervention, e.g., septal myectomy or mitral valve replacement, is another optional treatment. However, such surgical treatments carry a significant operative mortality and have not been shown to alter the natural history of the disease. See, "Permanent Pacing As Treatment For Hypertrophic Cardiomyopathy," by Kenneth M. McDonald et al., *American Journal of Cardiology*, Vol. 68, pp. 108-110, July 1991.

The value of dual chamber cardiac pacing and treatment of patients suffering from HOCM has been recognized in the literature. Modern multiple-mode, dual-chamber cardiac pacemakers are designed to maintain AV synchrony for damaged or diseased hearts that are unable to do so on their own. For example, a DDD pacemaker has electrical connections to both the atrium and the ventricle, senses electrical signals in both chambers of the patient's heart, and delivers atrial pacing stimuli in the absence of signals indicative of natural atrial depolarization, and ventricular pacing stimuli in the absence of signals indicative of natural ventricular depolarization. Such a dual chamber pacemaker maintains the AV synchrony of the heart by delivering ventricular pace pulses at a controlled AV interval following each atrial event.

Studies have indicated that patients suffering from HOCM may benefit from a pacing treatment wherein a ventricular pace pulse is delivered in a specific timed relationship to the sensed or paced atrial depolarization. In particular, if the right ventricular apex is paced before spontaneous atrio-ventricular conduction activates the left ventricle, the ventricular and ventricular septal activation patterns are altered. This reduces leftward motion of the Septum, thereby reducing the LVOT obstruction and subaortic pressure gradient.

The literature uniformly acknowledges the potential advantages of synchronized A-V pacing for HOCM patients, stressing the importance of achieving ventricular capture. Causing "complete ventricular capture" is important to obtain the above-described septal movement, while selecting the longest AV delay that results in complete ventricular capture is important in order to maximize the atrial contribution to ventricular filling. See U.S. Patent No. 5,507,782, filed March 17, 1994, Method and Apparatus For Dual Chamber Cardiac Pacing, assigned to Medtronic, Inc., and the literature articles referenced therein. The delivered pace pulse should provide "pre-excitation," i.e., depolarization of the ventricular apex before the septum. This altered pattern of septal contraction, as well as optimal left ventricular filling, is generally recognized as being important to this mode of pacemaker treatment. Further, it appears to be established that such synchronized AV pacing provides HOCM patients a long term benefit, i.e., the benefit remains even after cessation of pacing, since such AV pacing causes a reduction in the obstruction of the LVOT which persists in sinus rhythm after cessation of pacing.

The literature suggests that the AV escape interval should be set at the longest duration that maintains ventricular capture at different exercise levels. See the above-cited McDonald article. It has been suggested that the AV escape interval which allows for maximal pre-excitation of the ventricle by the pacing pulse can be selected by determining the AV escape interval that produces the widest paced QRS complex duration. See "Impact of Dual Chamber Permanent Pacing in Patients With Obstructive Hypertrophic Cardiomyopathy With Symptoms Refractory to Verapamil and b-Adrenergic Blocker Therapy," by Fananapazir et al., *Circulation*, Vol. 8, No. 6, June 1992, pp. 2149-2161.

In the referenced U.S. patent assigned to Medtronic, Inc., the pacemaker periodically checks to determine a value of intrinsic AV conduction time (AVC) and subtracts therefrom a ventricular sense offset interval (VSO) to get the AV escape interval. After a waveform of the ventricular depolarization resulting from complete capture is noted and recorded for comparison, the AV escape interval is set to a lengthened value, resulting in one or more ventricular sense events. The value of AVC is determined as the time difference between the atrial event and the sensed R-wave. Following this, the pacemaker AV escape interval is reduced further until the pacemaker finds an R wave with a waveform that indicates good capture. The difference between AVC and the capture value of A-V is VSO, and the pacemaker thereafter sets $AV = AVC - VSO$.

The prior art techniques for synchronous pacing of HOCM patients recognize the necessity to periodically evaluate the AV delay, or AV escape interval. The patient's spontaneous atrio-ventricular conduction time generally will change with heart rate, i.e., from rest to exercise. Moreover, simultaneous drug treatment such as beta blockers may also modify AV conduction time and require renewed evaluation of the AV delay. The

importance of periodically making an accurate determination of the optimized AV interval thus takes on significance. If the AV delay is adjusted to a value which is too short, in order to ensure complete ventricular capture, the atrial contribution to ventricular filling is compromised. However, if the AV escape interval is adjusted to too great a value, ventricular capture is compromised, and there may be episodes of no ventricular pacing or the ventricular pace may not contribute the best possible reduction of the LVOT obstruction. Accordingly, it is important in this therapy to be able to continuously or periodically adjust the AV escape interval to optimize it for HOCM therapy.

Accordingly, there is a substantial need for an improved system for treating patients having cardiomyopathy or certain forms of congestive heart failure, and a system for carrying out such treatment. The pacemaker of this invention embodies pacing the patient's ventricle in a timed relationship to the anticipated depolarization which would otherwise occur due to spontaneous atrio-ventricular conduction. While the preferred embodiment involves synchronized dual chamber pacing and adjustment of the AV escape interval, it is within the broader scope of the invention, as defined in the claims, to deliver ventricular pace pulses that have a controlled timing so as to optimize pre-excitation of the ventricle, whether or not the ventricular pace pulses are synchronized to atrial events. Further, while the preferred embodiment is illustrated in terms of treating HOCM, the system of this invention is also applicable to treatment of dilated cardiomyopathy and certain forms of congestive heart failure.

According to the present invention, there is provided a dual chamber pacemaker, having atrial sense means for sensing atrial signals from a patient, ventricular sense means for sensing ventricular signals from a patient, ventricular pace means for generating and delivering ventricular pace pulses to said patient's right ventricle, sync control means for controlling said pace means to generate and deliver a ventricular pace pulse at a controlled AV escape interval following a sensed atrial signal, said sync control means having AV_{esc} means for setting said AV escape interval, and adjustment means for adjusting said AV escape interval, characterized by:

said AV_{esc} means comprising fusion means for detecting the occurrence of fusion beats, rate means for determining a rate of occurrence of fusion beats over a plurality of pacemaker cycles, and
said adjustment means for adjusting said AV escape interval makes said adjustment as a function of said determined rate.

The pacemaker system of this invention is based on the observation that when a ventricular pace pulse is delivered with a timing that results in a fusion or near

fusion beat, there is a detectable change in the characteristics of the evoked QRS. In the practice in this invention, such fusion condition can be detected by discriminating a relative change in duration of the evoked QRS signal, a relative change in QRS amplitude, or a change in the QRS morphology, or a change in T-wave characteristics.

In accordance with a preferred embodiment of this invention, the pacemaker system detects fusion beats and monitors the number of fusion beats which occur over a predetermined time interval or number of pacemaker cycles, and determines whether this percentage is acceptable. The acceptable percentage may be zero, i.e., no fusion beats are acceptable, or it may be a suitable non-zero small percentage. When an unacceptable fusion percentage is determined, the pacemaker automatically adjusts AV delay to a lesser value, i.e., a value which restores continuous capture by delivered synchronous ventricular pace pulses. When the pacemaker operation has proceeded for a predetermined time or cycle interval without any determination of non-acceptable fusion beats, the pacemaker increments AV interval toward the fusion value, so as to continually adapt the value toward the longest possible value consistent with avoiding fusion. In another embodiment, the V-V escape interval of a non-tracking mode pacemaker is controlled to optimize pre-excitation of the ventricle.

EP-A-597 728 discloses a pacemaker having the features of the preamble of claim 1.

EP-A-600 631 is concerned with the development of a pacer for use in patents with cardiomyopathy. This device comprises means for determination of the natural AR interval and for adjusting the AV escape interval as a function of AR.

Figure 1 is a perspective representation of a pacemaker system according to this invention showing an implantable pacemaker connected to a patient's heart.

Figure 2 is a block diagram of a pacemaker system according to this invention, showing a pacemaker interconnected with an external programmer and with ECG leads.

Figure 3 is a block diagram of the primary functional components of a pacemaker system of this invention.

Figure 4A is a generalized flow diagram illustrating steps taken in synchronous pacing used in the pacemaker system in accordance with this invention, including adjusting AV escape interval for optimizing HOCM therapy; Figure 4B is a flow diagram of a generalized routine used by the pacemaker system of this invention in adjusting the AV escape interval for optimized HOCM therapy pacing.

Figure 5 is a representative data plot of QRS duration as a function of pacemaker AV interval.

Figure 6A is a detailed flow diagram of a routine of the pacemaker system of this invention for adjusting AV escape interval as a function of a determined percentage of detected fusion beats; Figure 6B is a simplified flow diagram showing steps for detecting the occur-

rence of a fusion beat.

Figure 7 is a simplified flow diagram of a routine of an alternative embodiment of the pacemaker system of this invention for adjusting V-V escape interval for providing pacing therapy in a non-tracking mode.

Figure 1 illustrates the external configuration of a dual chamber pacemaker 6, which is provided with a hermetically sealed enclosure 8, typically fabricated of biocompatible metal such as titanium. Mounted to the top of the enclosure 8 is a connector block assembly 12, which receives electrical connectors located on the proximal ends of leads 14 and 16. Lead 16 is an atrial pacing lead, carrying two electrodes 20 and 21. Electrodes 20 and 21 are used both to sense atrial depolarizations and to deliver atrial pacing pulses. Atrial pacing pulses may be delivered between electrode 20 and electrode 21 or between electrode 21 and the housing 8 of the pacemaker 6. Sensing of atrial depolarizations may occur between electrode 20 and electrode 21 or between either of electrode 20 and 21 and the housing 8 of the pacemaker 6.

Similarly, lead 14 represents a ventricular bipolar pacing lead, carrying two electrodes 28 and 29. As discussed above in conjunction with atrial lead 16, electrodes 28 and 29 are used to sense and pace the ventricle. Ventricular pacing may be accomplished between electrodes 29 and 28 or between electrode 29 and the conductive housing 8 of pacemaker 6. Sensing of ventricular signals, including depolarizations (QRS-waves) and repolarizations (T-waves) may be accomplished between electrodes 29 and 28 or between either of electrodes 29 and 28 and the housing 8 of the pacemaker 6.

As discussed in the present application, the preferred embodiments of the pacemaker 6 operate in a DDD or DDDR pacing mode, wherein pacing pulses are delivered to both atrium and ventricle and wherein atrial and ventricular depolarizations are both effective to inhibit delivery of the next scheduled pacing pulse in the chamber in which they are detected. While the present invention is believed optimally practiced in a pacemaker operating in DDD pacing mode, in some patients there may also be a benefit to operating the device in VDD or DVI mode, which provides ventricular pacing pulses synchronized only to sensed atrial depolarizations or only delivered to atrial pacing pulses, respectively, depending upon the specific underlying heart condition of the patient. However, DDD mode is expected to be the mode most widely used to practice the present invention.

Figure 2 illustrates the pacemaker 6 in block diagram form, coupled to a human heart 10, in conjunction with an external programmer/display apparatus corresponding to those typically employed to program modern, multi-programmable implantable pacemakers. Within the housing of the pacemaker are located the pacing circuitry 320, which includes circuitry performing all of the basic timing, stimulation and sensing functions

of a cardiac pacemaker and a microprocessor circuit 302, which controls the timing intervals provided by the pacing circuitry 320. Pacing circuitry 320 also includes a bidirectional telemetry circuit coupled to an antenna 334, allowing transmission of information from external programmer 4 into the pacemaker 6 to modify its parameters and allowing transmission of information from the pacemaker 6 to the external programmer 4, again generally corresponding to telemetry and programming systems presently existing in commercially marketed multi-programmable in implantable pacemakers.

The programmer 4 also includes a corresponding antenna 100 coupled to a telemetry/antenna driver circuit 102 which serves to demodulate telemetry signals received from antenna 334 of the pacemaker, and to apply them in parallel or serial digital format to input output (I/O) unit 108, where they in turn may be applied to a video monitor 112 via graphic interface 110, and/or provided to central processing unit 114 and/or printer 118. Microprocessor 114 controls the operation of the programmer/display apparatus, and is responsive to physician entered commands via keyboard 116, for controlling programming signals sent to the pacemaker, as well as for controlling operation of the video display 112 and printer 118. Also illustrated is an ECG interface 104, coupled to three ECG electrodes 106 which can be placed upon the patient's body. ECG interface 104 provides sensed electrograms to input/output device 108, where they in turn may be provided to the video display 112, the central processing unit 114 or the printer 118. The ECG capability is used for treatment according to the method of this invention for a patient who is available for initial or subsequent programming.

Figure 3 is a block functional diagram of the pacemaker illustrated in Figure 1, as connected to a human heart 10. The circuitry illustrated is all located within the conductive housing or can 8 of the pacemaker, as illustrated in Figure 1, and the bipolar leads 14 and 16 are illustrated schematically as coupled directly to the circuit. However, of course, in the actual device they would be coupled by means of removable electrical connectors inserted in the connector block 12, as illustrated in Figure 1.

The pacemaker is divided generally into a microcomputer circuit 302 and a pacing circuit 320. A pulse generator circuit 340 includes a ventricular pulse generator circuit coupled to the heart 10 by means of electrodes 29 and 28 on lead 14, as well as an atrial pulse generator circuit coupled to the heart 10 by means of atrial electrodes 20 and 21, located on lead 16. Similarly, pacing circuit 320 includes atrial and ventricular sense amplifiers in sense amplifier circuit 360, coupled to the atrium and ventricle by means of leads 14 and 16 as well. The ventricular sense amplifier provides for separate detection and identification of QRS-wave signals, in a known manner; it may also provide for detection and identification of T-wave signals. The atrial sense amplifier provides for respective identification of

P-waves and FFRS signals. The output circuit 340 and sense amplifier circuit 360 may contain pulse generators and sense amplifiers corresponding to any of those presently employed in commercially marketed cardiac pacemakers. Control of timing and other functions within the pacemaker circuit is provided by digital controller/timer circuit 330, which includes a set of timers and associated logic. Digital controller/timer circuit 330 defines the basic pacing interval of the device, which may take the form of an A-A escape interval initiated on atrial sensing or pacing and triggering atrial pacing at the expiration thereof, or may take the form of a V-V escape interval, initiated on ventricular sensing or pacing and triggering ventricular pulse pacing at the expiration thereof. Digital controller/timer circuit 330 similarly defines the A-V escape interval, AV_{esc}, discussed in detail below. The specific values of the intervals defined are controlled by the microcomputer circuit 302 by means of data and control bus 306. Sensed atrial depolarizations and FFRSs are communicated to the digital controller/timer circuit 330 on A event line 352; and ventricular depolarizations (QRS-waves) and repolarizations (T-waves) are communicated to the digital controller/timer circuit 330 on V event line 354. In order to trigger generation of a ventricular pacing pulse, digital controller/timer circuit 330 generates a trigger signal on V trig line 342. Similarly, in order to trigger an atrial pacing pulse, digital controller/timer circuit 330 generates a trigger pulse on a trig line 344.

Digital controller/timer circuit 330 also defines time intervals for controlling operation of the sense amplifiers in sense amplifier circuit 360. Typically, digital controller/timer circuit 330 will define an atrial blanking interval following delivery of an atrial pacing pulse, during which atrial sensing is disabled, as well as ventricular blanking intervals following atrial and ventricular pacing pulse delivery, during which ventricular sensing is disabled. Digital controller/timer circuit 330 will also define an atrial refractory period during which atrial sensing is disabled, this refractory period extending from the beginning of the A-V escape interval following either a sensed or paced atrial depolarization, and extending until a predetermined time following sensing of a ventricular depolarization or delivery of a ventricular pacing pulse. Digital controller/timer circuit 330 similarly defines a ventricular refractory period following ventricular sensing or delivery of a ventricular pacing pulse, which is typically shorter than the portion of the atrial refractory period following ventricular sensing or pacing. Digital controller/timer circuit 330 also controls sensitivity settings of the sense amplifiers 360 by means of sensitivity control 350. Control 350 is also utilized to generate timing windows for isolation and detection of portions of the received waves, e.g., FFRS signals from the atrial channel and R-wave and T-wave portions respectively from the ventricular channel.

In the embodiment illustrated in Figure 2, the pacemaker is provided with a piezo electric sensor 316

which is intended to monitor patient activity, in order to allow provision of rate responsive pacing, such that the defined pacing rate (A-A escape interval or V-V escape interval) increases with increased demand for oxygenated blood. Sensor 316 generates electrical signals in response to sensed physical activity which are processed by activity circuit 322 and provided to digital controller/timer circuit 330. Activity circuit 332 and associated sensor 316 may correspond to the circuitry disclosed in U.S. Patent No. 5,052,388, issued to Betzold et al., and U.S. Patent No. 4,428,378, issued to Anderson et al. Similarly, the present invention may be practiced in conjunction with alternative types of sensors such as oxygenation sensors, pressure sensors, pH sensors and respiration sensors, all well known for use in providing rate responsive pacing capabilities. Alternatively, QT time may be used as the rate indicating parameter, in which case no extra sensor is required. Similarly, the present invention may also be practiced in non-rate responsive pacemakers.

Transmission to and from the external programmer 4 illustrated in Figure 2 is accomplished by means of antenna 334 and associated RF transmitter and receiver 322, which serves both to demodulate received downlink telemetry and to transmit uplink telemetry. Crystal oscillator circuit 338 provides the basic timing clock for the circuit, while battery 318 provides power. Power on reset circuit 336 responds to initial connection of the circuit to the battery for defining an initial operating condition and similarly, resets the operative state of the device in response to detection of a low battery condition. Reference mode circuit 326 generates stable voltage reference and currents for the analog circuits within the pacing circuit 320, while analog to digital converter ADC and multiplexor circuit 328 digitizes analog signals and voltage to provide real time telemetry of cardiac signals from sense amplifiers 360, for uplink transmission via RF transmitter and receiver circuit 332. Voltage reference and bias circuit 326, ADC and multiplexor 328, power on reset circuit 336 and crystal oscillator circuit 338 may correspond to any of those presently used in current marketed implantable cardiac pacemakers.

Microcomputer circuit 302 controls the operational functions of digital controller/timer 330, specifying which timing intervals are employed, and controlling the duration of the various timing intervals, via data and control bus 306. Microcomputer circuit 302 contains a microprocessor 304 and associated system clock 308 and on processor RAM circuits 310 and 312, respectively. In addition, microcomputer circuit 302 includes a separate RAM/ROM chip 314. Microprocessor 304 is interrupt driven, operating in a reduced power consumption mode normally, and awakened in response to defined interrupt events, which may include delivery of atrial and ventricular pacing pulses as well as sensed atrial and ventricular depolarizations. In addition, if the device operates as a rate responsive pacemaker, a timed inter-

rupt, e.g., every cycle or every two seconds, may be provided in order to allow the microprocessor to analyze the sensor data and update the basic rate interval (A-A or V-V) of the device. In addition, in a preferred embodiment of the invention, the microprocessor 304 may also serve to define variable A-V escape intervals and atrial and ventricular refractory periods which may also decrease in duration along with decreases in duration of the basic rate interval. Specifically, the microprocessor is used to carry out the routines illustrated in Figures 4A, 4B, 5A and 5B.

The illustrated circuitry of Figure 3 is merely exemplary, and corresponds to the general functional organization of most microprocessor controlled cardiac pacemakers presently commercially available. It is believed that the present invention is most readily practiced in the context of such a device, and that the present invention can therefore readily be practiced using the basic hardware of existing microprocessor controlled dual chamber pacemakers, as presently available, with the invention implemented primarily by means of modifications to the software stored in the ROM 312 of the microprocessor circuit 302. However, the present invention many also be usefully practiced by means of a full custom integrated circuit, or any combination of hardware and software.

Referring now to Figure 4A, there is shown a generalized flow diagram of steps taken by a pacemaker system in accordance with this invention in performing synchronous pacing, with adjustment of AV_{esc} for optimal HOCM therapy. The steps of this flow diagram are suitably carried out by microcomputer circuit 302. This is a simplified flow diagram setting forth only steps pertinent to controlling AV_{esc}, and does not include many other steps and responses that occur during each cycle of a typical dual chamber pacemaker. The illustrated logic of Figure 4A recognizes that the intrinsic AV conduction time following an atrial pace pulse is greater than following a sensed atrial depolarization, by an amount described as "atrial sense offset", or ASO in referenced U.S. Patent 5,507,782. The AV_{esc} following an atrial pace is defined as PAV; the AV_{esc} following an atrial sense is defined as SAV; and PAV = SAV + ASO .

At block 401, the routine of Fig. 4A is waiting for what is expected to be an atrial event. When an event occurs, the routine goes to block 402 and determines whether there has been timeout of the atrial escape interval, A_{esc}. If yes, this indicates that an atrial pace (AP) should be delivered, and this is done at block 404. Following this, the routine sets AV_{esc} to PAV, and initiates timeout of AV_{esc}. Returning to 402, if there has been no timeout of A_{esc}, the pacemaker proceeds to 408, and determines whether there has been an early ventricular sense (VS). If yes, the routine branches to block 409 and resets the timing appropriately, whereafter it returns to block 401. However, as would normally be the case, if at 408 the event is not a VS, meaning that it has been an atrial sense (AS), the routine proceeds to

block 410 and sets AV_{esc} to the current value of SAV. Following this, the routine goes to 412 and initiates timeout of the atrial escape interval (A_{esc}), and timeout of the AV escape interval, AV_{esc} (either SAV or PAV). Then, at 414, the pacer waits for the next event, normally a ventricular event.

At 415, the pacemaker responds to an event by first determining whether the event was a timeout of AV_{esc}. If no, meaning that there was a ventricular sense, the pacemaker proceeds to block 417 and resets PAV and SAV to a shorter value which ensures capture by the next ventricular pace pulse. For example, each of these values can be decremented by 20 or 50 ms, to ensure that succeeding timeouts of AV_{esc} occur early enough for complete capture. It is to be noted, however, that the algorithms discussed below are designed to avoid an occurrence of VS, such that the pacemaker should rarely take this path.

If at 415 there has been a timeout of AV_{esc}, then the pacemaker proceeds to block 418 and delivers a V pace. Then, at block 419, the pacemaker determines whether it is programmed to go into the AV adjust routine. If no, the routine is done and it exits back to 401. If yes, the pacemaker goes to the adjust AV routine at block 420. Here, the pacemaker analyzes collected data, e.g., VP-FFRS time; FFRS duration; or FFRS or QRS amplitude. With this data in hand, the pacemaker system can adjust the values of PAV and SAV, in accordance with a predetermined algorithm for changing AV_{esc} so as to optimize resultant pre-excitation. Following this, the routine returns to block 401 and waits for the next atrial event.

Note that the pacemaker can be programmed for automatically monitoring AV data and adjusting AV_{esc} each pacemaker cycle, or these steps can be taken on some other periodic or user-programmed basis, within the scope of the invention. For an implanted pacemaker which is set to automatically adjust AV, the pacemaker goes directly to 420. Similarly, for a pacemaker system in accordance with this invention which adapted to be programmed specifically by a physician, the routine exits unless the programming sequence has been activated.

Figure 4B is a simplified flow diagram showing the primary steps of a generalized routine for controlling AV escape interval as a function of determined percentage. At 430, it is determined whether the pacemaker is programmed to go into the test to determine whether AV escape interval should be changed. The programmer may be permanently set to conduct a test repetitively, or may be programmed from an external programmer by a physician. Assuming that the pacemaker is so programmed, at 432 the pacemaker runs a routine to get the percentage fusion. This routine is illustrated in greater detail in connection with Figures 5, 6A and 6B. After this, at block 434, it is determined whether the percentage is less than a predetermined minimum, e.g., less than .5%, 1%, 2%, etc. If yes, meaning that the

number of fusion beats is acceptably low, the routine branches to block 440, and determines whether to increment AV escape interval. This decision is preferably made as a function of the detected percentage. For example, if the percentage is 0, the decision is made to increment, and at 442 AV is incremented by a small amount 2, e.g., 5 ms.

Returning to decision block 434, if the percentage is not less than the predetermined minimum, the routine goes to block 436 and determines a decrement amount 1 as a function of the detected percentage. Thus, for example, if the percentage is relatively high, 1 can be set to a relatively higher figure, e.g., in the range of 20-50 ms. If the percentage is lower, 1 may be more suitably set to a figure in the range of 5-10 ms. Then, at 438 AV is decremented by 1, and the routine exits.

Referring now to Figure 5, there is shown a plot of data representative of QRS or FFRS duration (ms) as a function of pacemaker AV interval (ms). As seen in Figure 5, the QRS duration is relatively low at higher AV intervals which are greater than the patient's intrinsic PR conduction time, i.e., where a VS occurs before timeout of AV_{esc}. However, as AV_{esc} is shortened, it comes into a fusion area where QRS increases and peaks; at shorter intervals, where a VP results in full capture, QRS duration is substantially constant at a value higher than the values corresponding to spontaneous QRSs. The knee portion between full capture and failure to capture is termed the fusion area, or range, and the ability to detect duration changes in this area provides the basis for one embodiment of this invention. As used herein, the term "fusion" embraces the entire range, including the lower portion of the range referred to as "onset of fusion." In the discussions of Figures 6A and 6B below, detection of fusion may be determined by examination of QRS duration to see whether operation is within the fusion range, or any part of it. Alternatively, fusion may be determined by comparing other QRS characteristics, such as morphology and amplitude. Additionally, fusion may be determined by detection of changes in the ventricular repolarization, or T-wave, as well as changes in the VP-QRS time, i.e., the time interval between delivery of a ventricular pace pulse and the evoked QRS.

Still referring to Figure 5, it is noted that there is a variation in the degree of fusion within the fusion range. Thus, there is maximal fusion toward the center of the range, and minimal fusion toward the upper and lower limits of the range. It is within the scope of the invention to measure the degree of fusion, and control as a function of the degree of fusion. For example, a beat with no greater than X% fusion can be deemed acceptable, such that the algorithm would allow a maximum of Y% of the beats to have greater than X% fusion.

Referring now to Figure 6A, the routine is initially entered at 640, where the AV interval is set equal to a nominal predetermined value. At 641 three routine variables are set equal to 0, namely PACECOUNT, FUSE-COUNT, and DECADECOUNT. Following this, the routine goes to block 642, and waits for an atrial event, either sense or pace. The pacemaker sets AV_{esc}, as illustrated in Figure 4A, and proceeds to block 644 where it waits for a V event, either sense or pace. At 646, if the V event has been a sense, the routine branches to 647 and sets the three routine variables to 0. Thereafter, at 648, the AV interval is decremented by a predetermined value Y, to bring the interval back to a shorter value so as to ensure synchronous pacing with capture. At 649 the pacemaker checks to see if the new value of AV interval is equal to or greater than a programmed value AV_{MIN} and adjusts the value if necessary at 650 before returning to the wait for the next atrial event.

If, at 646, it is determined that there has been a delivered ventricular pace pulse, then at 652 the variable PACECOUNT is incremented by 1. Then, at 653, the pacemaker system waits for an evoked response, and determines whether there has been a fusion beat. As discussed previously, fusion can be determined in a number of different ways. In the preferred embodiment, fusion is determined by detecting a significant decrease in duration of either the QRS waveform from the V sense channel, or the FFRS waveform from the A sense channel. Reference is made to Fig. 6B, and the discussion relating thereto. If fusion is detected, the variable FUSECOUNT is incremented at 654. Then, at 655 the value of PACECOUNT is compared to a predetermined number, e.g. 10. If PACECOUNT has not reached the predetermined number, the routine returns to 642. However, if it has, the routine goes to 657 and determines the percent of fusion beats in the last n cycles (e.g., 10), and whether this percentage is acceptable. If no, the routine branches to 658, resets the three routine variables to 0, and then at 659 decrements AV by a fixed amount indicated as Z. Z, for example, may be in the range of 20-50 ms, chosen to shorten AV interval so that it is safely short of the value where fusion has been detected.

Returning to 657, if the percent fusion occurrences is acceptable, e.g., there have been no fusion beats or less than the minimum acceptable percentage, the routine goes to 662 and sets PACECOUNT and FUSE-COUNT equal to 0. DECADECOUNT is incremented by 1, and then at 664 the DECADECOUNT is compared to a fixed number, illustrated as 6. A DECADECOUNT of 6 is seen to correspond to 60 cycles in this example. If the DECADECOUNT count has not reached 6, the routine returns to 642. However, if it has, this means that pacemaker activity has remained quiescent for a predetermined number of cycles, and the routine reacts by adjusting AV_{esc} so as to search for a fusion value of the AV interval. The routine goes to 666 and increments AV_{esc} by a variable T, suitably 5 ms, which takes it toward the fusion range. DECADECOUNT is set back to 0. Then, at 668 AV is compared to AV_{MAX}, and is set equal to AV_{MAX} at 670 if required. It is seen that in this

manner, as long as no unacceptable fusion percentage is detected, the AV interval is periodically incremented toward a fusion value, thereby providing a closed loop control for keeping the value of AV escape interval within a short range. The range of AV_{esc} has a high limit at about the onset of fusion, and is dynamic so as to track with time any changes in the patient's intrinsic conduction interval.

Referring now to Figure 6B, there is shown a simplified flow diagram for determining whether a fusion beat has occurred. At 670, the pacemaker gets the QRS or T-wave, and examines the wave at 672 to obtain a wave characteristic. As discussed above, this characteristic may be duration, as illustrated in Figure 5, or any other signature type characteristic. The data reflecting the characteristic are stored with the identification CHAR1. Then, at 674, the pacemaker compares the characteristic data just obtained (CHAR1) with the characteristic data of the prior signal designated as CHAR2. Based on this comparison, at 676, the pacemaker makes a determination as to whether or not a fusion beat has just occurred. Then, CHAR 2 is set equal to the just obtained CHAR 1 at 678 or 679, for use during the next cycle. The steps of obtaining characteristics at 672 are accomplished by use of standard hardware, preferably also using digital processing techniques. For determining QRS width, or duration, this signal is processed to determine when it first rises to a predetermined level, and when it falls back below such level. Amplitude is suitably measured by either a simple peak detector or other standard amplitude detection circuitry. For getting the time of VP-QRS, a standard edge detector may be utilized in circuit 330 to sense when the leading edge of the QRS signal has reached the predetermined level, or has increased by a predetermined percentage. These standard circuits may be supplemented or replaced by known digital processing techniques carried out with the aid of microprocessor system 302. Note also that fusion can be determined by comparing the wave characteristic with a standard wave, i.e., a reference characteristic, taken from a full capture wave evoked by a ventricular pace pulse delivered after a short AV_{esc}.

It is to be noted that while the preferred embodiment has been illustrated in terms of determining the percentage of fusion beats that is acceptable, similar arrangements are within the scope of the invention. Thus, the algorithm for determining whether the number of fusion beats is acceptable or non-acceptable may involve any desired degree of complexity. For example, the determination may be made on the basis of total accumulated fusion beats over a predetermined time interval, e.g., on a daily basis. Alternatively, the percentage of fusion beats that is acceptable may be adjusted in accordance with monitored patient history, and likewise the adjustment following a determination of an unacceptable fusion rate may be varied as a function of patient history.

While the preferred embodiments of the invention

have been described with reference to dual chamber pacemakers, and control of the AV escape interval, the therapy provided by the pacemaker of this invention can also be provided by a pacemaker system which is operating in a non-tracking, or asynchronous mode. For example, in dual chamber pacemakers with a "Modeswitching" feature, the pacing mode is automatically changed from an atrial tracking mode (VDD, DDD, DDDR) to a non-tracking mode (DDIR or VVIR) upon detection of an atrial arrhythmia. In these situations, the pacemaker cannot track the atrial signal because the atrial rate is too high; and if AV conduction is intact, the pacemaker does not pace the ventricle because the intrinsic conduction is too fast and the ventricular pace pulse is inhibited. However, when a pacemaker is in a single chamber ventricular (VVI, VVIR) or dual chamber non-tracking mode (DDI, DDIR), the pacemaker system can nonetheless perform an analogous operation to the dual chamber therapy described above, except that the pacemaker system controls ventricular pacing escape interval (V-V_{esc}) rather than AV_{esc}. In such an embodiment, V-V_{esc} is initially shortened to correspond to a relatively high ventricular rate when tracking is not available, and with time V-V_{esc} is lengthened until fusion occurs. Thus, the algorithm is basically the same as for the above examples where AV_{esc} is modified, except control is through the V-V escape interval.

Referring to Figure 7, there is shown a simplified flow diagram for carrying out single chamber mode pacing therapy for patients with cardiomyopathy. It is noted that the pacemaker system monitors the atrial rate each cycle, although this is not shown in the diagram of Fig. 7. At 702, it is determined whether the atrial rate is greater than a maximum rate, such that it is too high. If no, the system branches to synchronous operation. However, if the atrial rate is found to be too high, or some other arrhythmia is detected at 702, the routine goes to block 704 and sets V-V_{esc} to a minimum value. Note that in a more sophisticated flow diagram the escape interval may be gradually ramped toward the minimum value, corresponding to a maximum asynchronous rate. At 706, the pacemaker waits for an event, and at 708 determines whether the event has been a timeout of a V-V_{esc}. If no, meaning that a natural ventricular depolarization was sensed, V-V_{esc} is reset at 709; if the arrhythmia is continuing, the routine returns to wait at block 706. However, if there has been a timeout, a ventricular pace pulse is delivered at 712, and then at 714 the pacemaker system determines whether this has resulted in a fusion beat. If no, the routine branches through 718, where periodically V-V_{esc} is incremented by 1. This increment can be done cyclically, or every N cycles, or by any other programmed arrangement. If fusion has been determined, at block 716 the pacemaker decrements V-V_{esc} by subtracting 2. By this arrangement, the pacemaker varies the rate of the delivered asynchronous pulses so as to optimize pre-excitation in the same manner as discussed above

for dual chamber-atrial tracking mode therapy. Following block 716 or 718, the routine checks to see if the arrhythmia is still present. If the pacemaker determines, at block 720, that the arrhythmia is over, then the program branches back to block 702.

It is noted that the embodiment of Figure 7 can be practiced with alternative techniques for determining when V-V$_{esc}$ should be adjusted. Thus, steps 714 and 716 can be eliminated, the routine periodically increasing V-V$_{esc}$ at 718 until a VS occurs, whereupon V-V$_{esc}$ is decremented to regain pacing. Thus, the scope of the Figure 7 embodiment is not limited to the preferred technique of detecting the occurrence of fusion in order to control the timing of delivered pace pulses.

Claims

1. A dual chamber pacemaker, having atrial sense means (20,21) for sensing atrial signals from a patient, ventricular sense means (28,29) for sensing ventricular signals from a patient, ventricular pace means (340) for generating and delivering ventricular pace pulses to said patient's right ventricle, sync control means (302) for controlling said pace means to generate and deliver a ventricular pace pulse at a controlled AV escape interval following a sensed atrial signal, said sync control means having AV$_{esc}$ means for setting said AV escape interval, and adjustment means for adjusting said AV escape interval, characterized by:

    said AV$_{esc}$ means comprising fusion means for detecting the occurrence of fusion beats, rate means for determining a rate of occurrence of fusion beats over a plurality of pacemaker cycles, and
    said adjustment means for adjusting said AV escape interval makes said adjustment as a function of said determined rate.

2. The pacemaker system as described in claim 1, said rate means having percentage means for determining the percentage of fusion beats over a plurality of pacemaker cycles, further comprising means for comparing said percentage to a predetermined minimum, and wherein said adjusting means adjusts said AV escape interval in response to a determination that said percentage is less than said predetermined minimum.

3. The pacemaker system as described in claim 2, wherein said adjustment means decrements said AV interval by a predetermined amount in response to a determination that said percentage is greater than said predetermined minimum.

4. The pacemaker system as described in claim 3, comprising means for adjusting said predetermined amount as a function of said determined fusion percentage.

5. The pacemaker system as described in claim 3, comprising means for periodically incrementing said AV escape interval by a second predetermined amount which is less than said first predetermined amount.

6. The pacemaker system as described in claims 1-5, comprising programmer means for programming operation of said fusion means, said rate means and said adjustment means.

7. The pacemaker system as described in claims 1-5, where said fusion means and said adjustment means are continually operative.

8. The pacemaker system as described in claim 7, wherein said rate means comprises first rate means for detecting a first fusion occurrence rate over a first predetermined number of pacemaker cycles, and second rate means for detecting a second fusion occurrence rate over a second predetermined number of pacemaker cycles.

9. The pacemaker system as described in claim 8, wherein said adjustment means has decrement means for decrementing said AV escape interval as a function of said first fusion occurrence rate, and increment means for incrementing said AV escape interval as a function of said second fusion occurrence rate.

Patentansprüche

1. Zweikammer-Schrittmacher mit

    einer atriellen Wahrnehmungseinrichtung (20, 21) zum Erfassen von atriellen Signalen eines Patienten,
    einer ventrikulären Wahrnehmungseinrichtung (28, 29) zum Wahrnehmen von ventrikulären Signalen des Patienten,
    einer Ventrikel-Stimuliereinrichtung (340) zur Erzeugung und Abgabe von Ventikel-Stimulationsimpulsen an den rechten Ventrikel des Patienten,
    eine Synchronsteuereinrichtung (302) zum Steuern der Stimuliereinrichtung zur Erzeugung und Abgabe eines Ventrikel-Stimulationsimpulses mit gesteuertem AV-Escapeintervall im Anschluß an ein wahrgenommenes atrielles Signal, wobei die Synchronsteuereinrichtung eine AV$_{esc}$-Einrichtung zur Vorgabe des AV-Escapeintervalls sowie eine Einstelleinrichtung zum Einstellen des AV-Escapeintervalls aufweist, dadurch **gekennzeichnet,**

daß die AV$_{esc}$-Einrichtung eine Fusionseinrichtung zum Erfassen des Auftretens von Fusionsschlägen sowie eine Frequenzeinrichtung zum Bestimmen der Frequenz des Auftretens von Fusionsschlägen über mehrere Schrittmacherzyklen aufweist, und

daß die Einstelleinrichtung zum Einstellen des AV-Escapeintervalls die Einstellung als Funktion der ermittelten Frequenz vornimmt.

2. Schrittmachersystem nach Anspruch 1, wobei die Frequenzeinrichtung eine Prozentualeinrichtung zum Bestimmen des Prozentsatzes an Fusionsschlägen über mehrere Schrittmacherzyklen und eine Einrichtung zum Vergleichen des Prozentsatzes mit einem vorgegebenen Minimum aufweist, und wobei die Einstelleinrichtung das AV-Escapeintervall in Abhängigkeit davon einstellt, daß der Prozentsatz als unter dem vorgegebenen Minimum liegend bestimmt wird.

3. Schrittmachersystem nach Anspruch 2, wobei die Einstelleinrichtung das AV-Intervall um einen vorgegebenen Betrag absenkt, wenn der Prozentsatz als über dem vorgegebenen Minimum liegend bestimmt wird.

4. Schrittmachersystem nach Anspruch 3, mit einer Einrichtung zum Einstellen des vorgegebenen Betrags als Funktion des ermittelten Prozentsatzes an Fusionen.

5. Schrittmachersystem nach Anspruch 3, mit einer Einrichtung zum periodischen Erhöhen des AV-Escapeintervalls um einen zweiten vorgegebenen Betrag, der unter dem ersten vorgegebenen Betrag liegt.

6. Schrittmachersystem nach einem der Ansprüche 1 bis 5, mit einer Programmiereinrichtung zum Programmieren des Betriebs der Fusionseinrichtung, der Frequenzeinrichtung und der Einstelleinrichtung.

7. Schrittmachersystem nach einem der Ansprüche 1 bis 5, wobei die Fusionseinrichtung und die Einstelleinrichtung kontinuierlich arbeiten.

8. Schrittmachersystem nach Anspruch 7, wobei die Frequenzeinrichtung eine erste Frequenzeinrichtung zum Ermitteln einer ersten Frequenz des Auftretens von Fusionen über eine erste vorgegebene Anzahl von Schrittmacherzyklen und eine zweite Frequenzeinrichtung zum Ermitteln einer zweiten Frequenz des Auftretens von Fusionen über eine zweite vorgegebene Anzahl von Schrittmacherzyklen aufweist.

9. Schrittmachersystem nach Anspruch 8, wobei die Einstelleinrichtung eine Dekrementiereinrichtung zum Verringern des AV-Escapeintervalls als Funktion der ersten Frequenz des Auftretens von Fusionen sowie eine Inkrementiereinrichtung zum Erhöhen des AV-Escapeintervalls als Funktion der zweiten Frequenz des Auftretens von Fusionen aufweist.

Revendications

1. Stimulateur cardiaque à deux chambres, comportant des moyens de détection auriculaire (20,21) pour détecter des signaux auriculaires provenant d'un patient, des moyens de détection ventriculaire (28,29) pour détecter des signaux ventriculaires provenant d'un patient, des moyens de stimulation ventriculaire (340) pour produire et délivrer des impulsions de stimulation ventriculaire au ventricule droit du patient, des moyens de commande de synchronisation (302) pour commander lesdits moyens de stimulation pour produire et délivrer une impulsion de stimulation ventriculaire avec un intervalle d'échappement auriculo-ventriculaire AV commandé, à la suite d'un signal auriculaire détecté, lesdits moyens de commande de synchronisation comportant des moyens de réglage de AV$_{esc}$ servant à régler ledit intervalle d'échappement AV, et des moyens de réglage pour régler ledit intervalle d'échappement AV, caractérisé en ce que :

> lesdits moyens de réglage de AV$_{esc}$ comprenant des moyens de fusion pour détecter l'apparition de battements de fusion, des moyens de détermination du rythme pour déterminer un rythme d'apparition de battements de fusion pendant une pluralité de cycles du stimulateur, et
> lesdits moyens de réglage servant à régler ledit intervalle d'échappement AV effectuent ledit réglage en fonction dudit rythme déterminé.
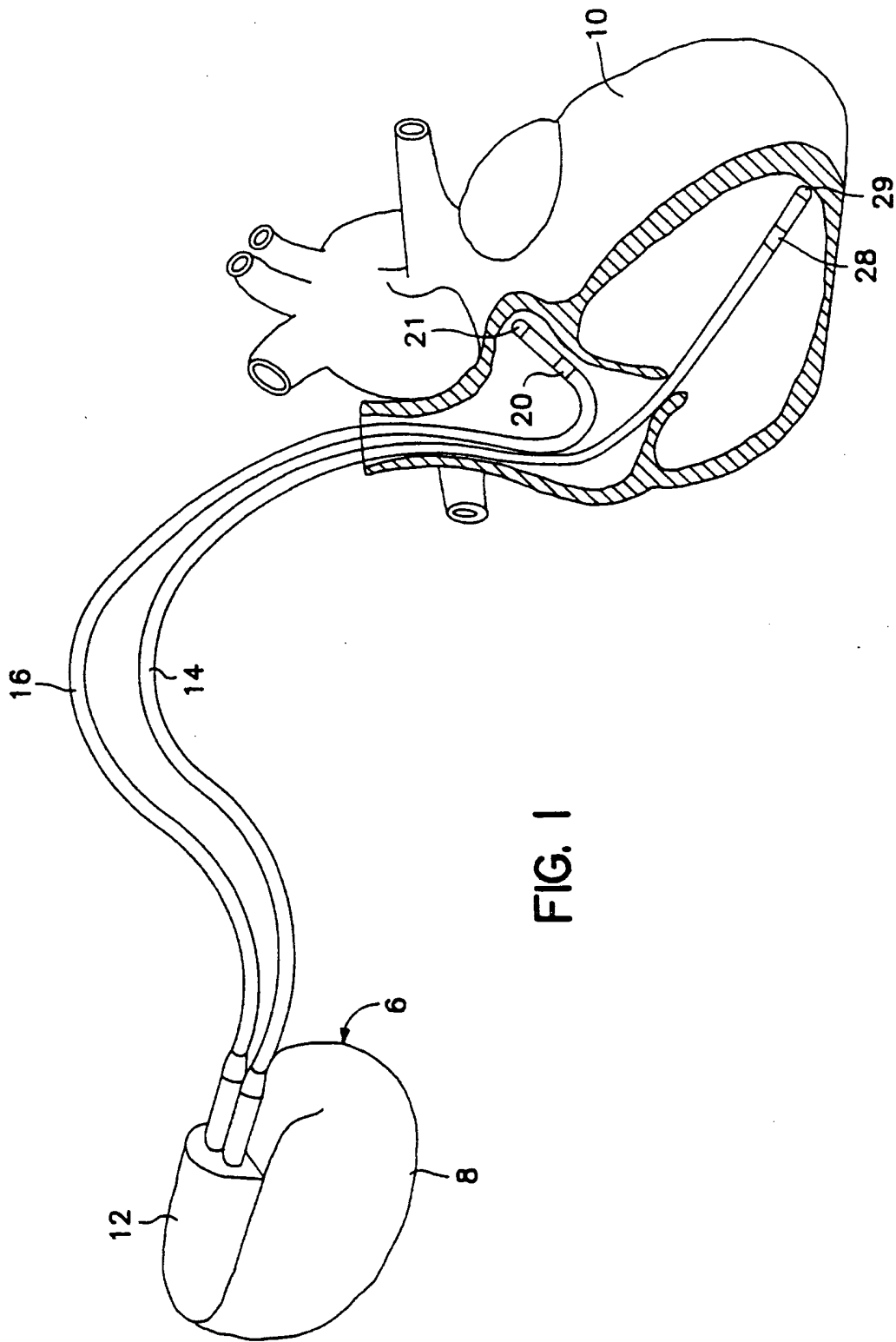
2. Système de stimulateur selon la revendication 1, dans lequel lesdits moyens de détermination du rythme comportent des moyens de détermination de pourcentage pour déterminer le pourcentage des battements de fusion sur une pluralité de cycles du stimulateur, comprenant en outre des moyens pour comparer ledit pourcentage à une valeur minimale prédéterminée, et dans lequel lesdits moyens de réglage règlent ledit échappement AV en réponse à une détermination du fait que ledit pourcentage est inférieur audit minimum prédéterminé.

3. Système de stimulateur selon la revendication 2, dans lequel lesdits moyens de réglage réduisent ledit intervalle AV d'une valeur prédéterminée en

réponse à une détermination du fait que ledit pourcentage est supérieur audit minimum prédéterminé.

4. Système de stimulateur selon la revendication 3, comprenant des moyens pour régler ladite valeur prédéterminée en fonction dudit pourcentage de fusion déterminé.

5. Système de stimulateur selon la revendication 3, comprenant des moyens pour incrémenter périodiquement ledit intervalle d'échappement AV, d'une seconde valeur prédéterminée qui est inférieure à ladite première valeur prédéterminée.

6. Système de stimulateur selon les revendications 1-5, comprenant des moyens formant programmateur pour programmer le fonctionnement desdits moyens de fusion, desdits moyens de détermination de rythme et desdits moyens de réglage.

7. Système de stimulateur selon les revendications 1-5, dans lequel lesdits moyens de fusion et lesdits moyens d'ajustement fonctionnent continûment.

8. Système de stimulateur selon la revendication 7, dans lequel lesdits moyens de détermination de rythme comprennent des premiers moyens de détermination de rythme pour détecter un premier rythme d'apparition de fusions pendant un premier nombre prédéterminé de cycles du stimulateur et des seconds moyens de détermination de rythme pour détecter un second rythme d'apparition de fusions pendant un second nombre déterminé de cycles du stimulateur.

9. Système de stimulateur selon la revendication 8, dans lequel lesdits moyens d'ajustement comportent des moyens de décrémentation pour décrémenter ledit intervalle d'échappement AV en fonction dudit premier rythme d'apparition de fusions, et des moyens d'incrémentation pour incrémenter ledit intervalle d'échappement AV en fonction dudit second rythme d'apparition de fusions.
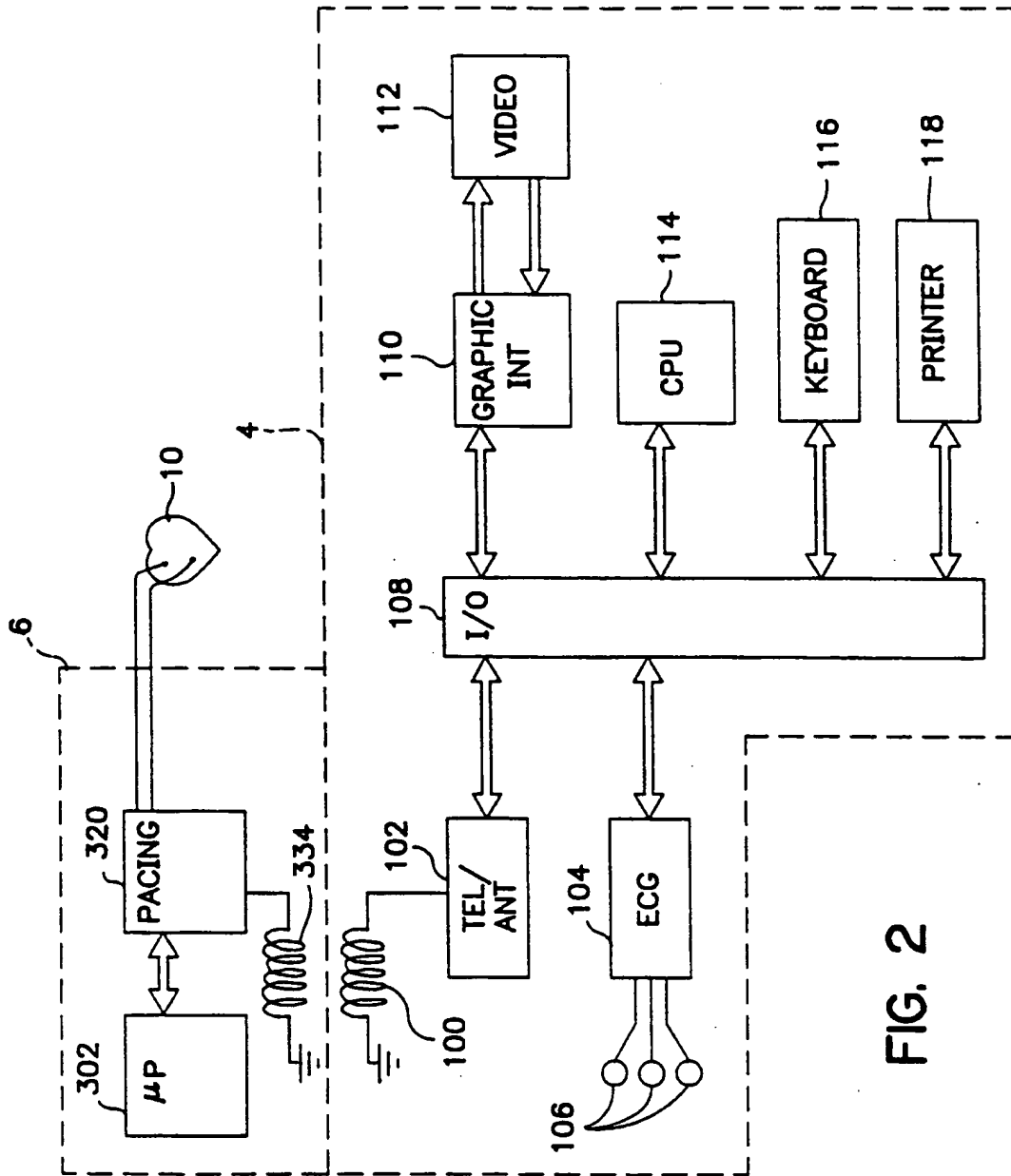
FIG. I

FIG. 2
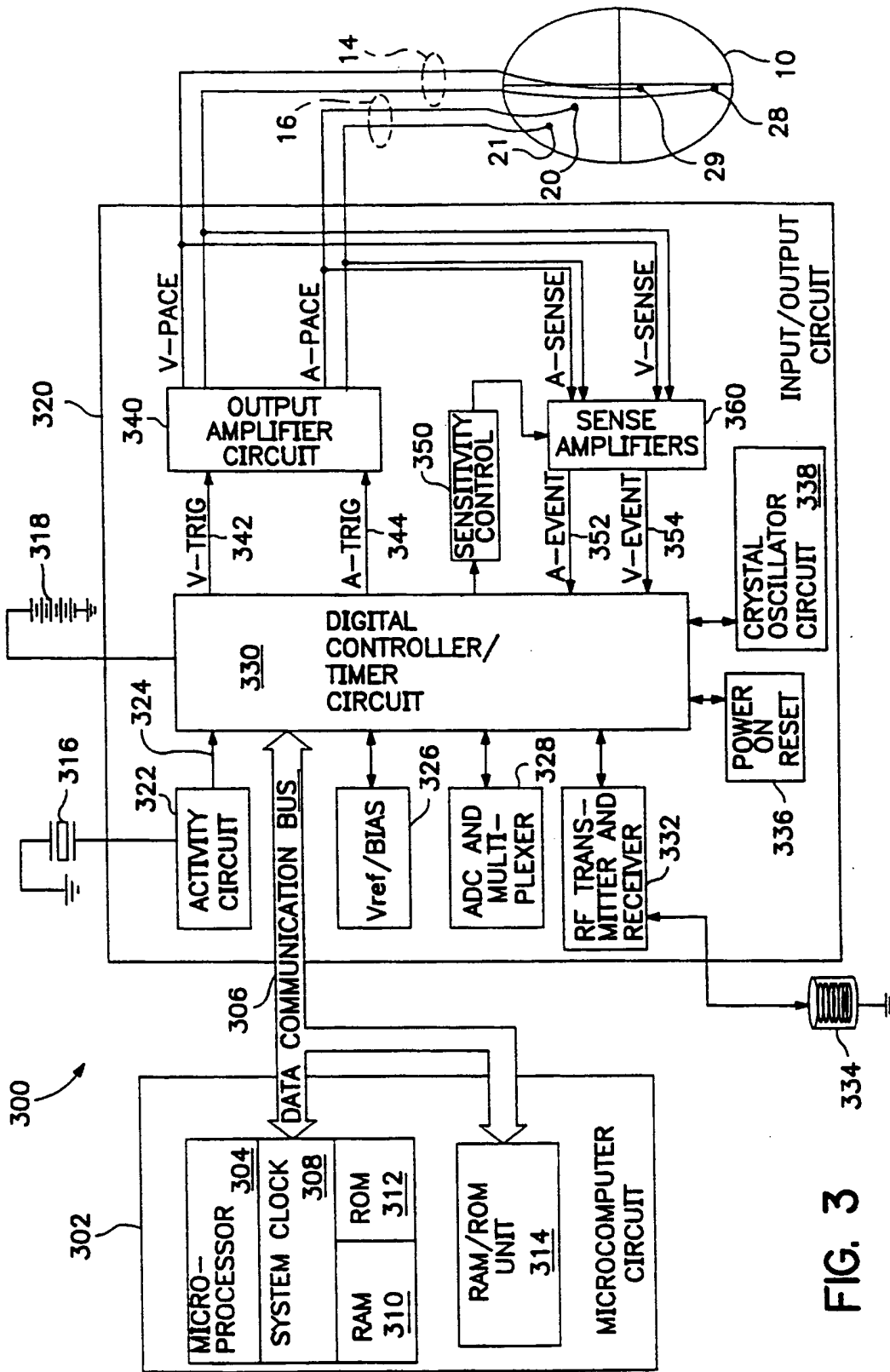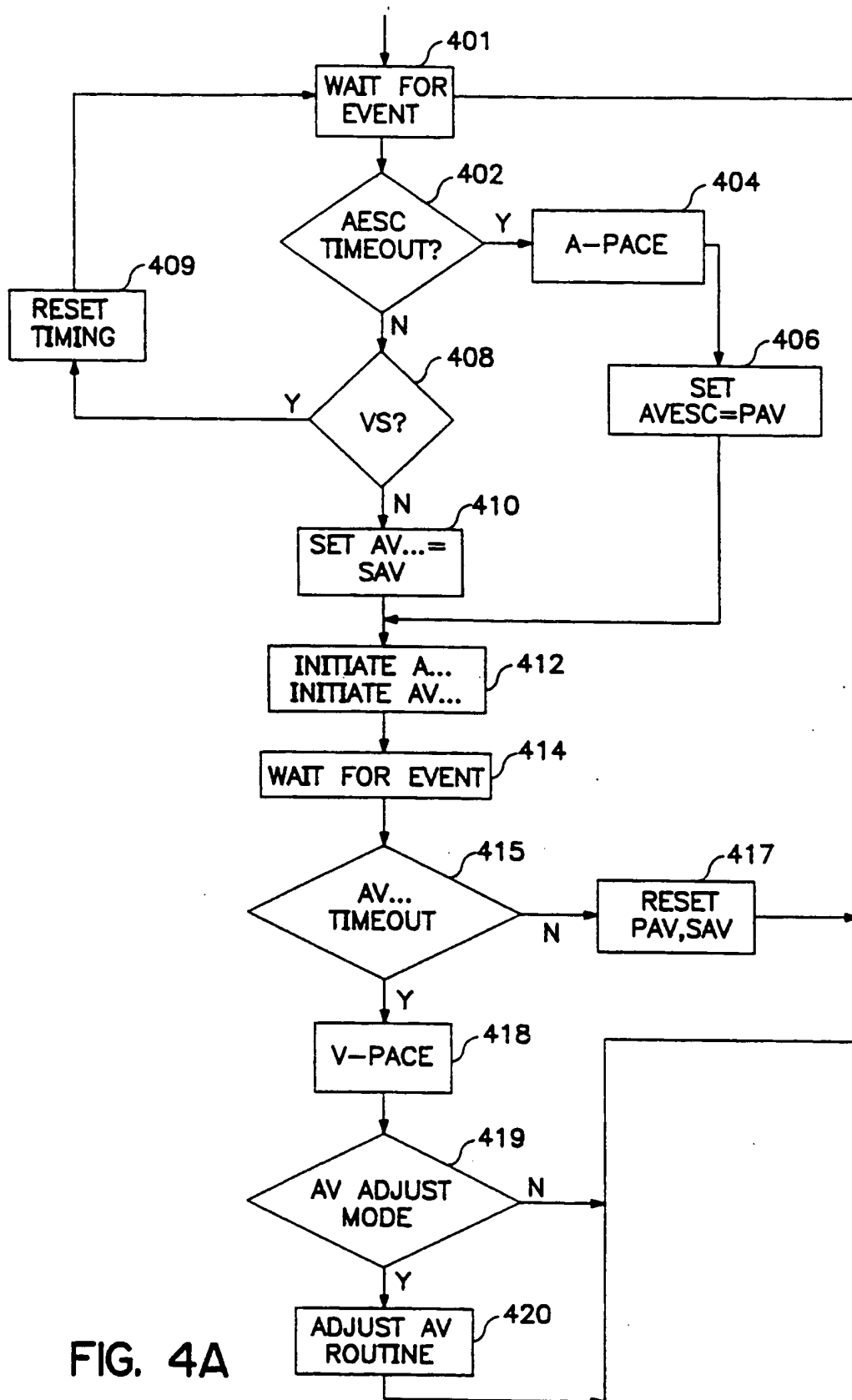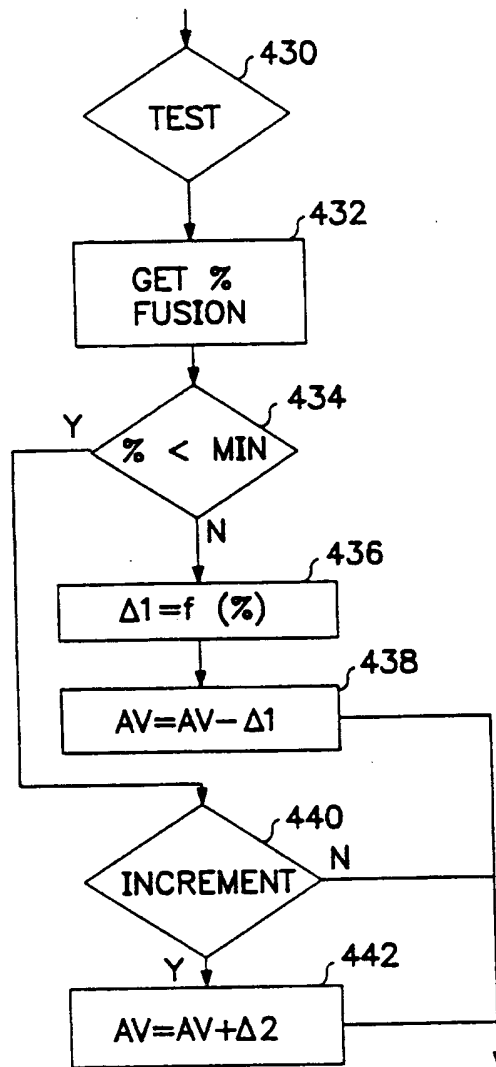
FIG. 3

FIG. 4A

FIG. 4B

GET QRS/T WAVE ~670

GET WAVE CHAR
STORE CHAR 1 ~672

653

COMPARE
CHAR 1,CHAR 2 ~674

676

FUSION

Y

N

CHAR 2=CHAR 1 ~678

679

CHAR 2=CHAR 1

TO 654

TO 655

FIG. 6B

MAX FUSION

FUSION RANGE

ONSET OF FUSION

160
140
120
100
80

QRS DURATION, ms.

150 160 170 180 200

PACEMAKER AV INT., ms.

FIG. 5

INITIALIZE
AVnom=Xms
AV=AVnom — 640

PACECOUNT=0
FUSECOUNT=0
DECADECOUNT=0 — 641

WAIT FOR ATRIAL EVENT;HANDLE — 642

AV=AVmin — 650

WAIT FOR VENTRICULAR EVENT — 644

V SENSE — 646

PACECOUNT=0
FUSECOUNT=0
DECADE-COUNT=0 — 647

AV=AV-Y — 648

1V≥AVmin — 649

PACECOUNT=PACECOUNT+1 — 652

FUSION — 653

FUSECOUNT=FUSECOUNT+1 — 654

AV=AVmin — 659

AV=AVmax — 670

PACECOUNT ≥10 — 655

%FUSION ACCEPTABLE — 657

N

PACECOUNT=0
FUSECOUNT=0
DECADECOUNT=0 — 658

Y

AV≤AVmax — 668

AV=AV+T
DECADE-COUNT=0 — 666
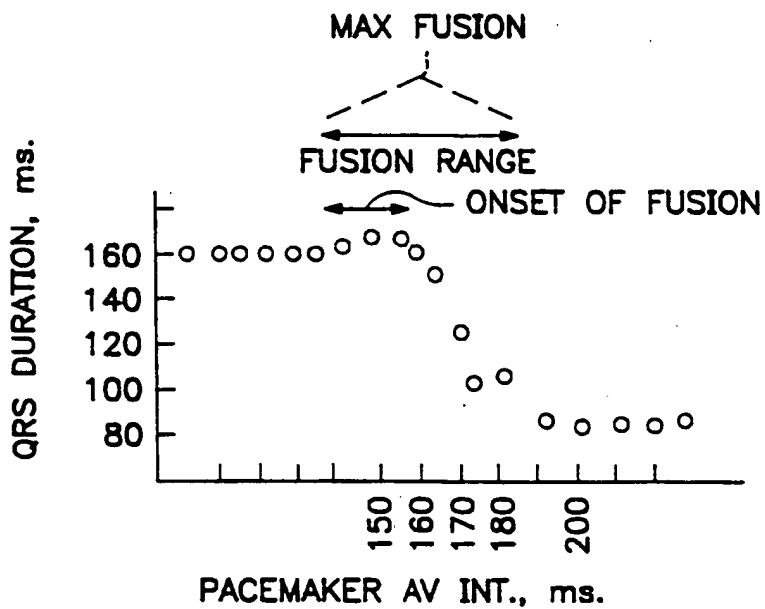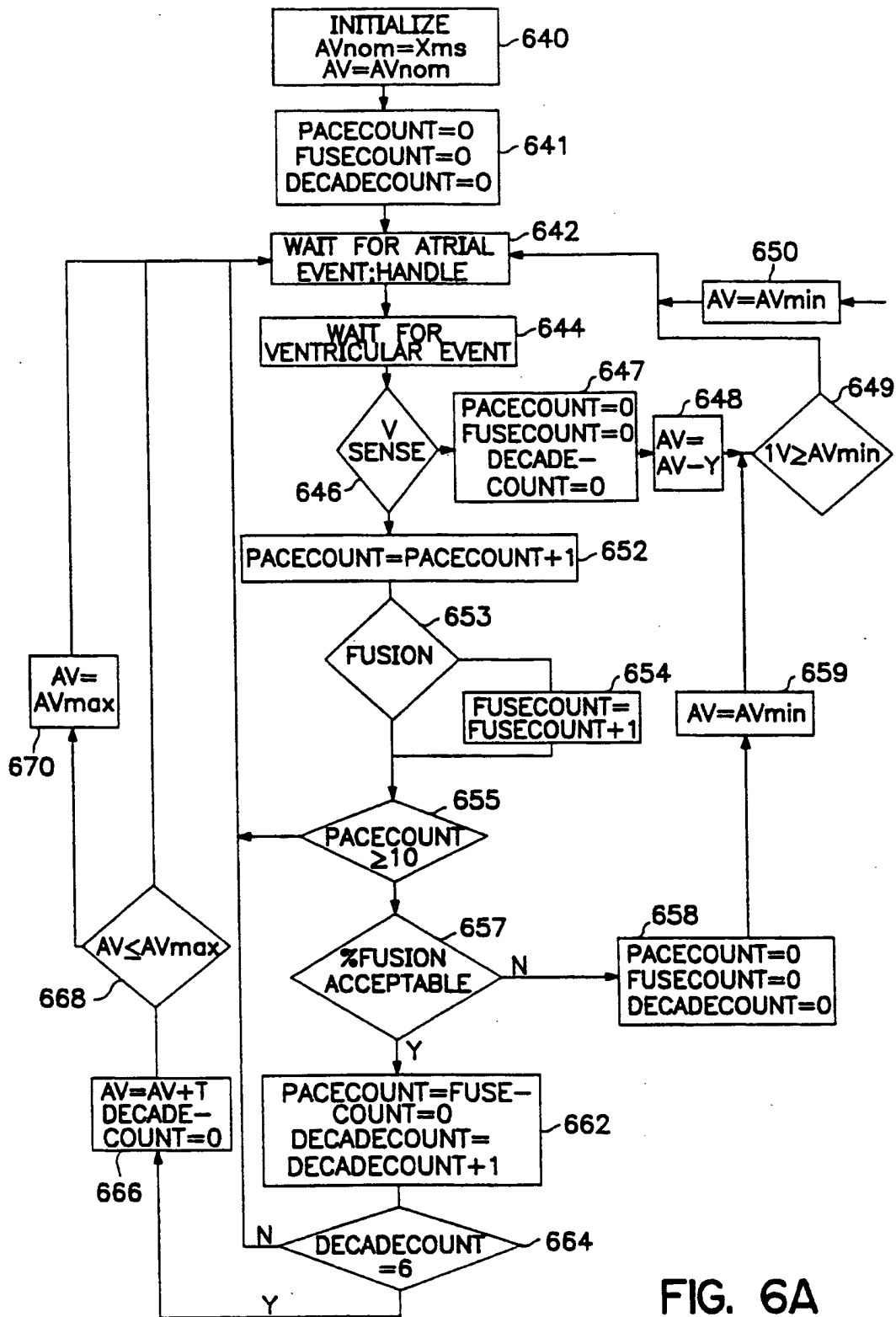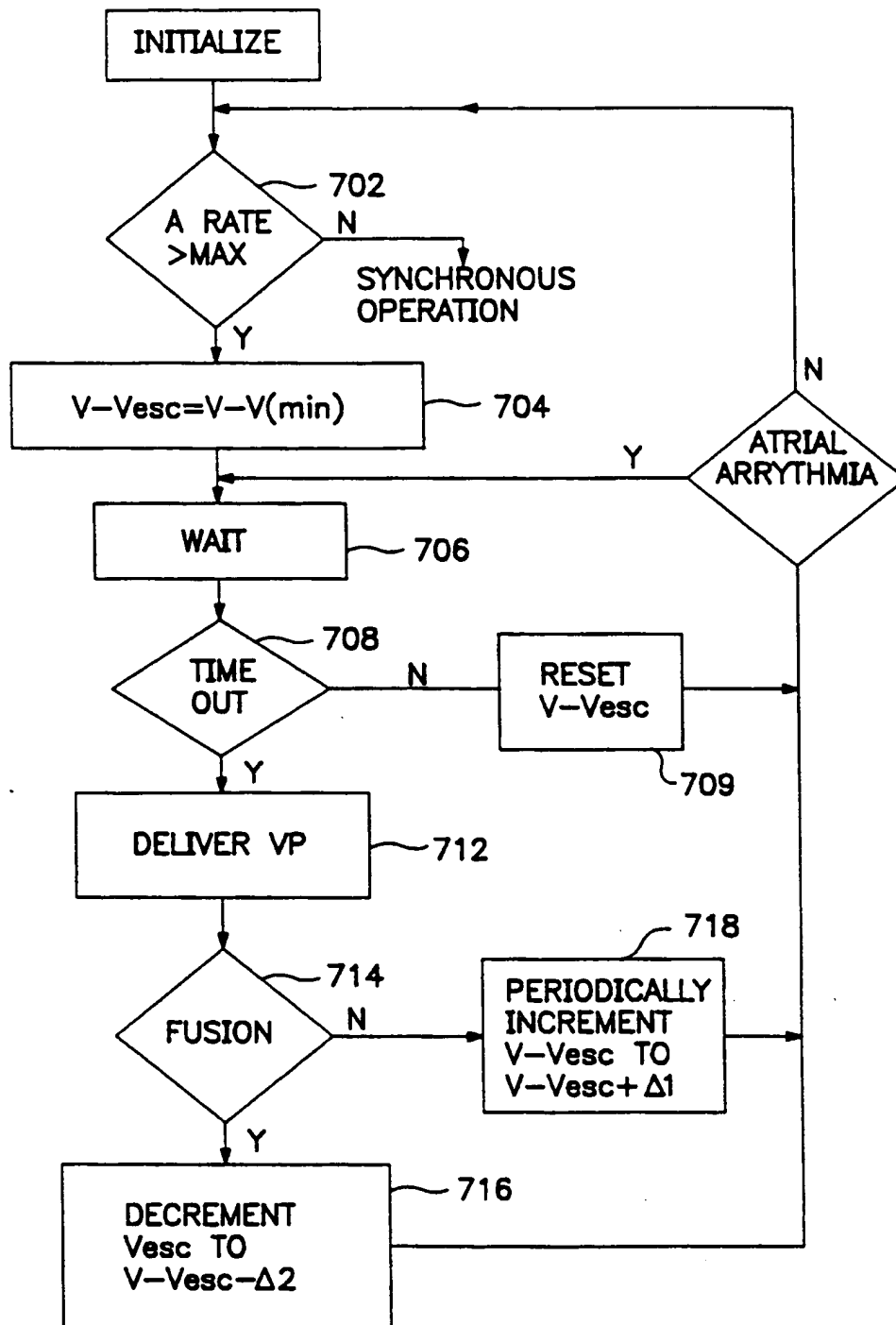
PACECOUNT=FUSE-COUNT=0
DECADECOUNT=
DECADECOUNT+1 — 662

N

DECADECOUNT =6 — 664

Y

FIG. 6A

FIG. 7

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